Limits on the evolution of galaxies from the statistics of gravitational lenses

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ABSTRACT

We use gravitational lenses from the Cosmic Lens All-Sky Survey (CLASS) to constrain the evolution of galaxies since redshift $z \sim 1$ in the current ΛCDM cosmology. This constraint is unique as it is based on a mass-selected lens sample of galaxies. Our method of statistical analysis is the same as in Chae (2003). We parametrise the early-type number density evolution in the form of $(1+z)^{\nu_n}$ and the velocity dispersion as $(1+z)^{\nu_v}$. We find that $\nu_n = -0.11^{+0.82}_{-0.89}$ (1σ) if we assume $\nu_v = 0$, implying that the number density of early-type galaxies is within 50% to 164% of the present-day value at redshift $z = 1$. Allowing the velocity dispersion to evolve, we find that $\nu_v = -0.4^{+0.5}_{-0.4}$ (1σ), indicating that the velocity dispersion must be within 57% and 107% of the present-day value at $z = 1$. These results are consistent with the early formation and passive evolution of early-type galaxies. More stringent limits from lensing can be obtained from future large lens surveys and by using very high-redshift quasars ($z \gtrsim 5$) such as those found from the Sloan Digital Sky Survey.

Subject headings: gravitational lensing - cosmology: theory - dark matter - galaxies: structure, evolution

1. INTRODUCTION

Currently there are about 70 multiply-imaged systems due to galactic mass scale gravitational lenses. The statistics of gravitational lenses depend on three key ingredients, namely, the cosmology, the number density of potential lenses as a function of redshift and the dynamical properties of galaxies (e.g., velocity dispersions and the surface mass densities).

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Gravitational lenses hence encode information of the cosmology, the galaxy mass profiles and the evolution history of galaxies. At present, the lens sample is too small to constrain all the ingredients simultaneously. Most previous studies concentrated on constraining the cosmological constant assuming non-evolving populations of lenses (e.g., Fukugita et al. 1992; Kochanek 1996; Helbig et al. 1999). Under this assumption, the most recent lens statistics study of Chae et al. (2002) finds that the lens statistics are best-fitted by a present-day matter density of $\Omega_{\rm m,0} \approx 0.3$ and a cosmological constant of $\Omega_{\Lambda,0} \approx 0.7$. This result is consistent with results from a variety of other studies, including the cosmic microwave background radiation (e.g., de Bernardis et al. 2000; Spergel et al. 2003), Type Ia supernovae at cosmological distances (e.g., Riess et al. 1998; Perlmutter et al. 1999), and the large-scale structures in the universe (e.g., Peacock et al. 2001).

In light of the convergence of the cosmological model, it becomes important to use gravitational lenses for a different purpose: to study the evolution of galaxies (their number density and dynamical properties) in the $\Omega_{\rm m,0} = 0.3, \Omega_{\Lambda,0} = 0.7$ cosmology (hereafter ΛCDM). Lensing limits on galaxy evolution have been explored by Mao (1991), Mao & Kochanek (1994), Rix et al. (1994), and Jain et al. (2000), all of which used optically-selected lenses. Lensing is sensitive to the evolution of galaxy properties as the lensing probability is $\propto n\sigma^4$, while separations are $\propto \sigma^2$; here n is the number density and σ is the velocity dispersion of typical lenses. For example, (for a fixed cosmological model) a decreasing number density of galaxies with redshift(z) lowers the lensing rate and the mean redshift of lenses while a decreasing velocity dispersion with z lowers the lensing rate, the mean lens redshift and the mean angular size of image separations. Therefore, through a careful analysis of the lens redshifts, image separations and lensing probability we can constrain the evolution of the number density and dynamical properties of galaxies.

Most lensing galaxies are massive early-type galaxies as they dominate the lensing cross-sections due to their larger central mass concentrations. Gravitational lenses therefore provide a unique mass-selected sample to study the evolution of early-type galaxies, independent of and complementary to the traditional redshift surveys of galaxies (e.g., Fried et al. 2001; Im et al. 2002). This is a much debated research area. There exist two different views on the formation and evolution of early-type galaxies, namely a monolithic collapse model (Eggen, Lynden-Bell, & Sandage 1962) and a merger hypothesis (Toomre & Toomre 1972). In the monolithic collapse model, early-type galaxies are thought to have formed rapidly at high redshift and then evolve passively to the present-day. The merger model is a natural consequence of the hierarchical structure formation theory. Semi-analytic implementations of this model predict a continuous formation of ellipticals and hence a certain fraction of massive early-type galaxies must have formed since $z \sim 1$ (e.g. Kauffmann 1996; Baugh et al. 1996; Kauffmann et at. 1999); the fraction depends on the assumed cosmology and other

assumptions and is typically one third or more (for more, see §4). An observational way of probing galaxy evolution is using redshift survey of galaxies. However, no consensus has been reached either with this method. For example, Kauffmann, Charlot, & White (1996) found rapid evolutions in the number density of ellipticals while Schade et al. (1999) advocated the opposite conclusion using similar samples (see §4 for more details).

The purpose of this work is to use data from the Cosmic Lens All-Sky Survey (CLASS) to provide independent constraints on galaxy evolution. As we were completing this work, a complementary study has been carried out by Ofek, Rix, & Maoz (2003); their results are compared with our results in §2.

2. DATA, METHOD AND RESULTS

We use data from the Cosmic Lens All-Sky Survey (CLASS) for our study. The survey is described extensively in Myers et al. (2003) and Browne et al. (2003). We refer the readers to those papers for details, and here we only give a brief summary. The CLASS well-defined statistical sample contains 8958 radio sources including 13 multiply-imaged sources.[3] The advantage of the CLASS survey is that it uses very well-defined observational selection criteria and does not suffer from the effect of dust extinction in lenses. It is also the largest completed survey for gravitational lenses, so it is the best sample for our purposes.

We assume the galaxy population is described by a Schechter luminosity function (LF),

$$n(L)\, d\left(\frac{L}{L_\star}\right) = n_\star \left(\frac{L}{L_\star}\right)^\alpha \exp(-L/L_\star) d\left(\frac{L}{L_\star}\right). \qquad (1)$$

Lensing galaxies are modelled as singular isothermal ellipsoids, which are described by two parameters, the velocity dispersion and the axial ratio (or equivalently, the ellipticity). The galaxy luminosity is related to the velocity dispersion via

$$\frac{L}{L_\star} = \left(\frac{\sigma}{\sigma_\star}\right)^\gamma. \qquad (2)$$

We divide galaxies into two populations, namely the early-type (ellipticals and S0's) population and the late-type population and assume that each population is described by its own LF. The parameter values we take are identical to those in Chae et al. (2002) (see also Chae 2003 for the details of the analysis and further results); we refer the readers to those two

[3]The rest of ~ 7000 CLASS sources contain further 9 multiply-imaged sources which, however, do not fall into our statistical sample (Myers et al. 2003; Browne et al. 2003).

papers. In particular, we adopt the type-specific LFs based on the galaxy classifications from the Second Southern Sky Redshift Survey (SSRS2: Marzke et al. 1998); see Chae (2003) for the details. Our adaptation of maximum likelihood analyses (Kochanek 1993) is identical to that of Chae et al. (2002) and Chae (2003). Under the ΛCDM cosmology we test two simple models of the evolution of early-type galaxies. The evolution of late-type galaxies is not considered, as we cannot obtain any useful limits due to the small number of late-type lens galaxies in the current sample (i.e. 1 or 2).

In the first model we adopt, we assume that the shape of the luminosity function (α) is a constant given by the SSRS2 (Chae 2003) and the non-evolving (characteristic) velocity dispersion $\sigma_\star$ (defined in eq. 2) is a constant to be determined from the data, but the (characteristic) number density of galaxies (defined in eq. 1) evolves as a function of redshift; we choose a power-law evolutionary shape of $1+z$,

$$n_\star(z) = n_{\star,0}(1+z)^{\nu_n}, \tag{3}$$

where $n_{\star,0}$ is the present-day value. The no-evolution model corresponds to $\nu_n = 0$. Fig. 1 shows confidence limits on the parameter ν_n and $\sigma_\star$. The χ^2 in Fig. 1 refers to $-2\ln\mathcal{L}$ where $\mathcal{L}$ is the likelihood function (Chae et al. 2002; Chae 2003). As one can see, the lens statistics are consistent with a no-evolution model in a ΛCDM cosmology at 1σ level. We find $\nu_n = -0.11^{+0.82}_{-0.89}$; namely, the number density of galaxies at redshift $z = 1$ cannot be smaller by a factor of two or larger by 64% than the present day number density. From Fig. 1 the non-evolving characteristic velocity dispersion is $\sigma_\star = 199^{+19}_{-16}$ km s$^{-1}(1\sigma)$. This value is in good agreement with the values from recent analyses of lensing statistics assuming no evolution of galaxies (Chae et al. 2002; Chae 2003; Davis, Huterer, & Krauss 2003).

In the second model, we allow the velocity dispersion $\sigma_\star$ (as well as the number density) to vary as a function of redshift:

$$\sigma_\star(z) = \sigma_{\star,0}(1+z)^{\nu_v}, \tag{4}$$

where $\sigma_{\star,0}$ is the present-day characteristic velocity dispersion. The no-evolution model corresponds to $\nu_v = 0$. Fig. 2 shows the limits in the parameter space of ν_n, ν_v and $\sigma_{\star,0}$. Fig. 2(a), (b) and (c) are the three projected parameter planes. Fig. 2(d) shows the limits in the plane of ν_v and $\sigma_{\star,0}$ based only on the image separations and the available lens redshifts (6 of them) of the nine single-galaxy induced multiply-imaged systems (see Section 3.1 of Chae 2003), namely without using the lensing rate [see below for a discussion of the Fig. 2(d)]. The contours shown on each plane represent 68%, 90%, 95% and 99% confidence levels for one parameter.

The contours in Fig. 2(a) are elongated parallel to a line $\nu_n + 4\nu_v$ = constant. This is because along the $\nu_n + 4\nu_v$ = constant line the optical depth ($\propto n\sigma^4$) is a constant. In other

words, there is a degeneracy in determining the evolutions of the velocity dispersion and the number density from the optical depth alone. Notice, however, that the degeneracy is in part broken by the observed image separations as a function of redshift. The 1σ limits on the two evolutionary indices are: $\nu_n = 0.7^{+1.3}_{-1.4}$ and $\nu_v = -0.4^{+0.5}_{-0.4}$. The limit on ν_v is particularly interesting: lensing statistics demand that the velocity dispersion for an $L_\star$ galaxy at $z = 1$ must be between 57% and 107% of the present-day value. This implies that dynamically, the population of lensing galaxies cannot be much different from the present-day population. From Fig. 2(b) or (c) the characteristic velocity dispersion of the present-day early-type population is $\sigma_{\star,0} = 223^{+38}_{-36}$ km s^{-1} (1σ). This value has a relatively large uncertainty and is consistent with the value for the non-evolving case shown in Fig. 1. However, it is of interest to note that the best-fit value of $\sigma_{\star,0}$ is somewhat larger than the non-evolving value. This is then consistent with the best-fit value of ν_v being negative.

Recently, Ofek et al. (2003) have used the redshifts of the lensing galaxies in moderate-size source-redshift(z_s)–limited samples to constrain the galaxy mass evolution. Our work is different as we use the well-defined uniform CLASS sample and we include all the lensing information (lensing rate, image separations and lens redshifts). Notice that our sample (13 lenses in total) includes 6 systems with both lens and source redshifts measured while the Ofek et al. (2003) samples have up to 17. They also conclude that there is little evidence for rapid evolution of early-type galaxies. They parameterize the evolutions in different forms from ours. But equivalently, they find that at 95% confidence level, $\sigma_\star$ at $z = 1$ should be at least 63% of the present value; this is similar to our 1σ limit. Despite the small number of the measured redshifts in our sample our limits on the evolution of $\sigma_\star$ are relatively strong because of the additional constraint of the lensing rate. This can be seen from the comparison of Fig. 2(c) and (d). Without the lensing rate, we have $\nu_v = 0.2^{+0.6}_{-1.0}$ [Fig. 2(d)], which is significantly broader. The Ofek et al. (2003) limit on the number density evolution is given by $d\log_{10} n_\star(z)/dz = +0.7^{+1.4}_{-1.2}$, translating into a 1σ lower limit of the number density of lenses at $z = 1$ of 30% of the present value; our limit (57%) is significantly stronger because of the strong effects of the lensing rate. Our results are consistent with an early-formation/passive-evolution picture (e.g. $z_{\rm formation} \gtrsim 2$) of early-type galaxies, as also inferred from studies of the fundamental plane of lensing galaxies (see Kochanek et al. 2000; Rusin et al. 2003).

3. DISCUSSIONS

We have used the statistical properties of the CLASS strong lens sample (i.e., the rate of multiple-imaging and the image separations as a function of redshift) to constrain the evolution of galaxies. The lens sample is unique as it is mass-selected and hence the

constraints obtained from it are independent of those from redshift surveys. The method we use is based on Chae et al. (2002) and Chae (2003) and has some uncertainties, such as the adopted luminosity function of early-type galaxies and the redshift distribution of the source population in the CLASS survey (see Chae 2003 for details). However, these uncertainties are smaller than those arising from the moderate-size CLASS sample of lenses.

We find that the (comoving) number density of lensing galaxies at redshift $z = 1$ must be within 50% to 164% of the present-day number density; their characteristic velocity dispersion also must be within 57% and 107% of the present value. The lensing statistics are therefore consistent with a slow evolution of galaxies in both their number density and their dynamical properties. These results are inconsistent with very fast evolution of early-type galaxies, where the number of early-types at $z = 1$ is only 20%-40% or less of the present-day values (e.g., Lin et al. 1999; Fried et al. 2001; Wolf et al. 2003). Our results are, however, consistent with several other studies, in particular the study based on the Hubble Space Telescope observations of the Groth Strip (Im et al. 2002) where there find a number density evolution of $n(z) \propto (1+z)^{-0.86\pm0.68}$ (see their Table 6) in the same underlying cosmology. In the Standard Cold Dark Matter model with $\Omega_{\rm m,0} = 1$, the number density of bright ellipticals at $z = 1$ is predicted to be a factor of 2-3 smaller than the local value (Kauffmann 1996; Baugh, Cole & Frenk 1996), inconsistent with our results. However, the evolution of galaxies is expected to be slower in the ΛCDM cosmology. Indeed, our results are consistent with the modest evolution out to redshift ~ 1 predicted by Kauffmann et al. (1999; see their Fig. 9) for the same cosmology. Quantitatively, for ellipticals with a stellar mass $\gtrsim 10^{10} M_\odot$, the space density at $z = 1$ is about 30% lower than the present day value in the fiducial model of Cole et al. (2000). This result is robust to changes in the amount of star formation occurring in bursts at high redshift (C. Baugh, private communication; Baugh et al. 1996). Our results are consistent with these predictions.

The effects of galaxy evolution on the lens statistics will be more dramatic for very high-redshift quasars ($z \gtrsim 5$, Fan et al. 2003). For a source at $z = 5$, half of the multiple-imaging cross-section (with separations between 0.3 to 5 arcseconds) is contributed by galaxies with redshifts greater than 1.2 if there was no evolution of galaxies. Hence the lensing probability will be reduced significantly if the comoving number density of early-type galaxies is much smaller at redshifts $z \gtrsim 1$ compared with the local number density. A large sample of very high-redshift quasars is therefore an independent and effective way of probing galaxy evolution.

The lensing constraints on the galaxy evolution are already quite competitive compared with those from other methods. However, they still suffer from the small number of lenses (13) in our CLASS statistical sample. With planned upgrades in major radio instruments

(such as eVLA and e-Merlin), it is possible to obtain a radio lens sample that is an oder of magnitude larger. When such a sample becomes available, the lensing constraint will become more stringent and more physical evolution (rather than our toy) models can be tested.

We thank I. Browne and C. Baugh for discussions and the anonymous referee for constructive comments. KHC acknowledges support from the Astrophysical Research Center for the Structure and Evolution of the Cosmos (ARCSEC) which was established under the KOSEF SRC program. KHC also acknowledges the hospitality provided by the Jodrell Bank Observatory during the summer of 2003.

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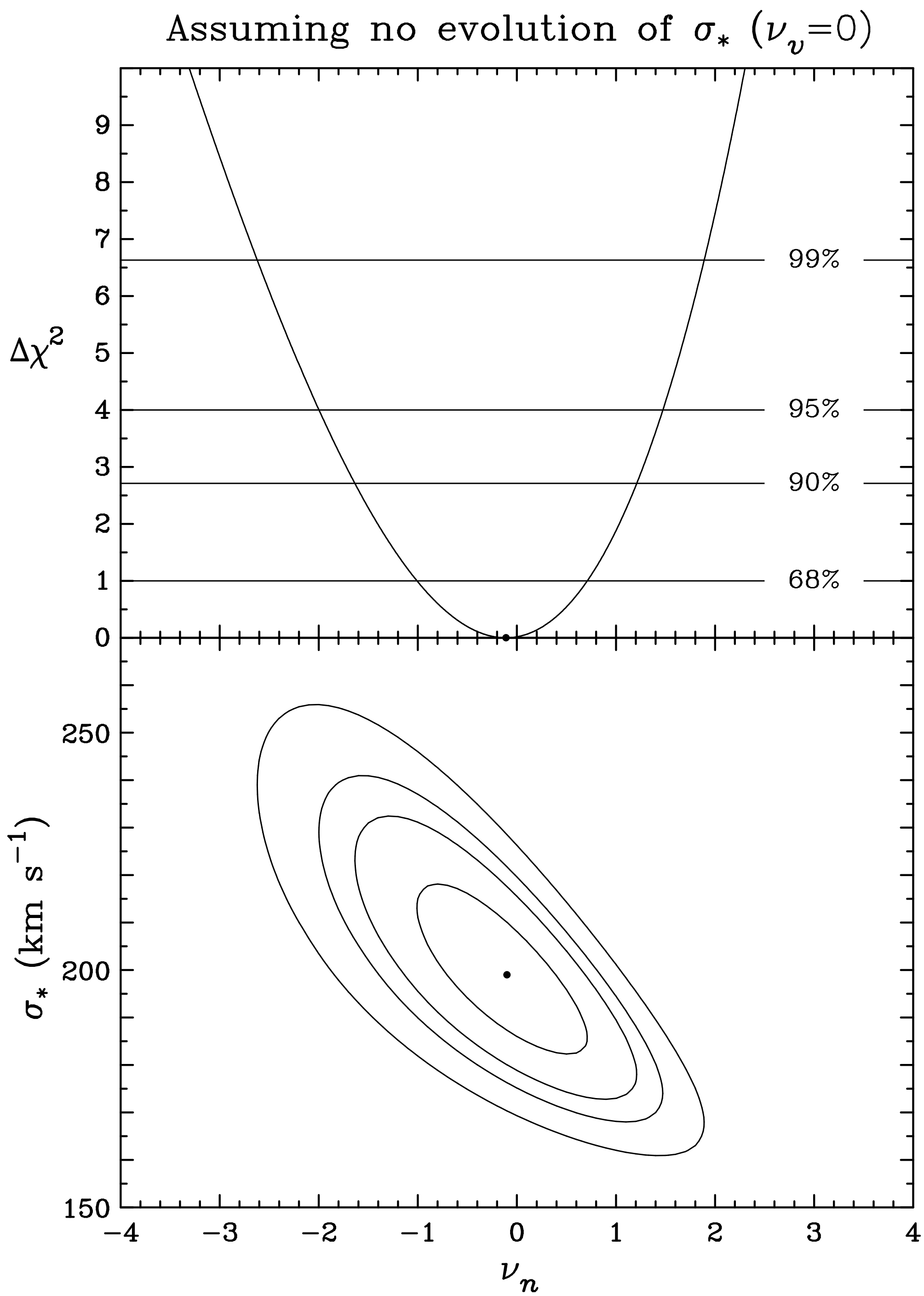

Fig. 1.— Confidence limits on the number-density evolutionary index for early-type galaxies, ν_n (see eq. 3), assuming no evolution of the velocity dispersion. The lower panel shows the likelihood contours in the ν_n and $\sigma_\star$ plane, with the solid dot indicating the peak of the likelihood function. The upper panel shows $\Delta\chi^2$ as a function of ν_n where we have marginalized $\sigma_\star$. Here χ^2 is defined as $-2\ln\mathcal{L}$ where $\mathcal{L}$ is the likelihood function.

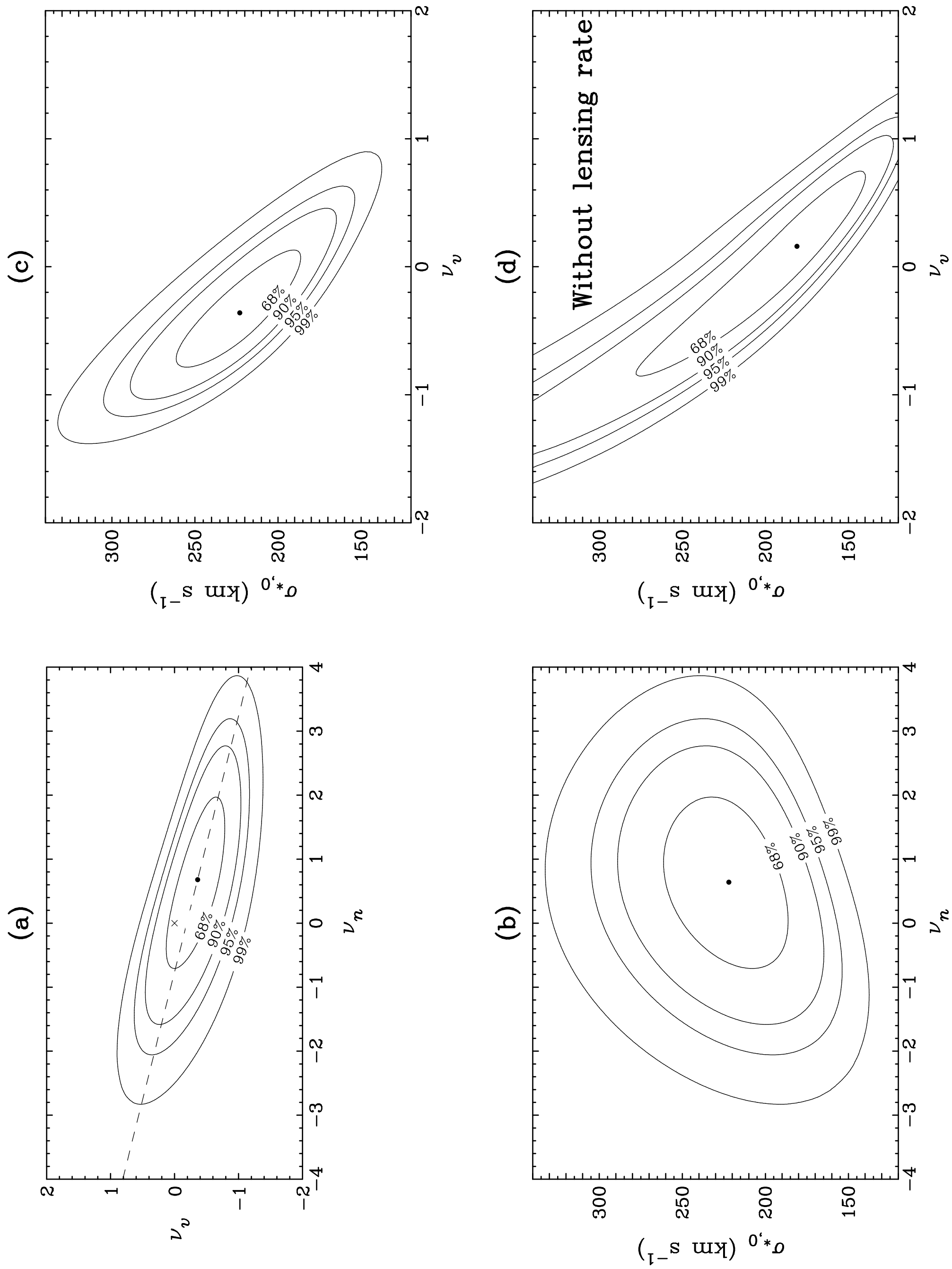

Fig. 2.— Confidence limits on the number density evolution index, ν_n, the velocity dispersion evolution index, ν_v (defined in eqs. 3 and 4), and the present-day velocity dispersion $\sigma_{\star,0}$. Panels (a), (b) and (c) show three different projections in the ν_n-ν_v, ν_n-$\sigma_{\star,0}$ and ν_v-$\sigma_{\star,0}$ planes, respectively; the third remaining parameter has been marginalized. In each panel, the solid dot indicates the peak of the likelihood function. In Fig. 2(a), the dashed line shows the line where the optical depth is kept as a constant ($\nu_n + 4\nu_v$ = constant), while the origin (marked by a cross) corresponds to the no-evolution case. Fig. 2(d) shows the likelihood contours on ν_v and $\sigma_{\star,0}$ where we do not incorporate the lensing rate information in our maximum likelihood calculation.